REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
02/05/2011

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
01/07/2006 TO 31/12/2009

4. TITLE AND SUBTITLE
Maneuvering in a Seaway

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-06-1-0879

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Beck, Robert F.
Sun, Jing

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Michigan
Division of Research and Development Administration
3003 South State St. 1058 Wolverine Tower
Ann Arbor, MI 48109-1274

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ONR Reg. Office Chicago-N62880
230 South Dearborn, Room 380
Chicago, IL 60604-1595

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Two codes have been developed to predict maneuvering in a seaway. The first uses a quasi-steady analysis with Fourier decomposition to determine the ship responses and find the optimum path for minimum motions. The second extends the existing body-exact strip theory (UMBEST) to arbitrary paths. Several different controllers, including a model predictive controller with constraint enforcement capability and a back-stepping nonlinear controller with desired stability margins, have been developed that will enable safe and effective ship maneuvering in a seaway while satisfying seakeeping constraints.

15. SUBJECT TERMS
Maneuvering in a seaway; seakeeping; ship control.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Robert F. Beck
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	16	734-764-0282

Contract Information

Contract Number	N00014-06-1-0879
Title of Research	Maneuvering in a Seaway
Principal Investigator	Robert F. Beck
Organization	University of Michigan

Final Letter Report

Technical Objectives

To develop a nonlinear, time-domain, blended-method code that is computationally fast and can be used to predict ship maneuvering in a seaway.

Technical Approach

We are developing a blended method to predict nonlinear ship motions while maneuvering in a seaway. The blended method uses the nonlinear Euler equations of motion and integrates the hydrostatic and Froude-Krylov exciting pressures over the exact, instantaneous wetted surface. The dynamic wave pressure up to the exact free surface can be used directly if known or a Wheeler stretching can be used in conjunction with linear potential waves. The radiation and diffraction forces are found from body-exact computations. The body-exact computations are all done in the time domain. Either a fourth-order Runge-Kutta scheme or a third-order Adams-Bashforth method is used for the time stepping.

In body-exact computations, the Laplace equation is solved at each time step subject to a body boundary condition on the exact position of the body and linearized free surface conditions (both dynamic and kinematic) on an apparent calm water plane defined by the intersection of the incident wave and the exact body position. The velocity of the body is the relative velocity between the body and the incident wave. Appropriate far field radiation conditions are also met. Desingularized sources are used above the free surface and flat panels with constant source strength are used on the body surface. Both a two-dimensional strip theory code and a three-dimensional body-exact code are available. The three-dimensional code is approximately 10-times slower computationally than the body-exact strip theory code, but it is useful to give insights into forward speed effects and the accuracy of the body-exact strip theory. Because the body-exact strip theory code (call UMBEST for University of Michigan Body-Exact Strip Theory) is much faster and for normal slender ships gives approximately the same motion predictions, we have focused on its development for the maneuvering problem.

Control systems have been developed to determine the control surface deflections that result in good path following in a seaway. A simulator capable of incorporating actual ship autopilots or helmsperson commands has been developed to facilitate the testing and evaluation of the proposed maneuvering/seakeeping time-domain model. Input to the code includes the ship geometry, inertial characteristics, desired seaway, relative wave heading, ship speed, and maneuvering path and control system description.

Summary

Work on the simplified quasi-steady model for a ship maneuvering in a seaway has been completed. The program easily runs in real time and returns the ship motions in six degrees of

freedom along a prescribed path given the ship speed, wave spectrum and primary wave direction.

Research is proceeding on developing a body-exact seakeeping/maneuvering code based on the University of Michigan Body-Exact Strip Theory code (UMBEST). UMBEST was originally developed for a ship traveling along a straight path. It has been verified and validated against experiments and other nonlinear seakeeping codes with very good results. The seakeeping/maneuvering code allows arbitrary paths and is presently running for zero forward speed. The forward speed version should be available shortly.

On the control side, three different control schemes have been designed, analyzed, and evaluated. Numerical and experimental platforms are established to provide tools to facilitate the control development and implementation. Progress has been made on developing an improved controller. By incorporating a Line of Sight (LOS) guidance parameter in the Model Predictive Control (MPC) controller design improved path following capabilities were realized. The controller is built on the integrated maneuvering and seakeeping control scheme which mimic good helmsman's behavior. The controller includes realistic limitations on maximum rudder deflection and rudder rate. The control algorithm is computationally fast and can be used for real time implementation for ship path following.

A MPC controller has been incorporated into UMBEST. The controller allows time-domain computations to proceed for all six degrees of freedom. Previous results were restricted to motions with stable equilibrium positions (heave, pitch and roll). In time-domain computations, surge, sway and yaw will drift off due to mean second order exciting forces and the lack of a "spring constant" term to return the motion to equilibrium. Having a good controller eliminates this problem.

Progress

The research under this contract is closely aligned with work being done under the MURI program entitled "Optimum Vessel Performance in Evolving Nonlinear Wave Fields," Contract No. N00014-05-1-0537 and work for the Theoretical Advisory Panel (TAP) on DDG1000 entitled "Support for the Theory Advisory Panel (TAP)," Contract No. N00014-09-1-0978. The MURI program requires a good maneuvering model in waves. The TAP program is primarily concerned with extreme motions (broaching and capsize) in large sea states. In large seas, the ship motions and course keeping are strongly coupled.

The progress under the different tasks is reported below:

Development of a Maneuvering/Seakeeping Simulation Tool

Robert F. Beck, University of Michigan

The long term goal of this project is to develop a maneuvering/seakeeping simulation tool for use in the MURI project entitled "Optimal Vessel Performance in Evolving Nonlinear Wave-Fields" and the TAP work. However, while that development was underway, the controls and path optimization group needed a maneuvering/seakeeping simulation model that they could work with. A quasi-steady model has been extended to realistic short crested seas. For a given wave spectrum and primary wave direction, the code returns the ship motions along a given path at a prescribed speed. The code has been very useful in the development of path following controllers in the MURI. This work is discussed in the paper by Li et al. (2010). In addition, the quasi-steady code was modified so that the user can input a position, time, speed and heading angle. The code will return the desired ship responses for that time, position, speed and heading. The output ship responses can include any of the six degree of freedom motions, the hydrodynamic forces, or derived responses such as accelerations at the bridge or helicopter pad.

An example of the use of the quasi-steady model in the path optimization for the MURI project is given in figures 1 – 2. Figure 1 shows the optimized path in a short crested sea coming from the left of the figure. Figure 2, shows the time history of the roll motion for the optimized path and the equivalent roll time history for the straight line path. The RMS roll reduction along the optimized path is 106% while the increase in travel time is 6%. Different starting and target points lead to similar results.

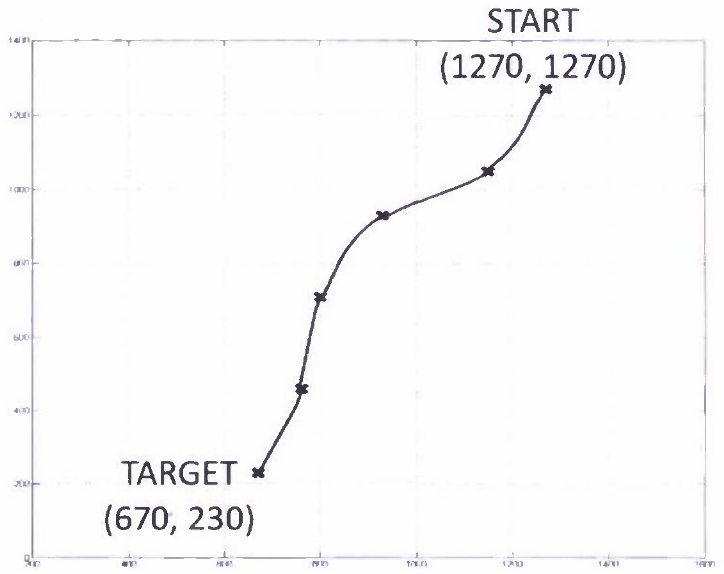

Figure 1. Optimum Path to Minimize RMS Roll: S-175 Container Ship, V= 20kts, Hs = 3.25m, Peak Period = 9.53s, Wave Direction = 30 degrees.

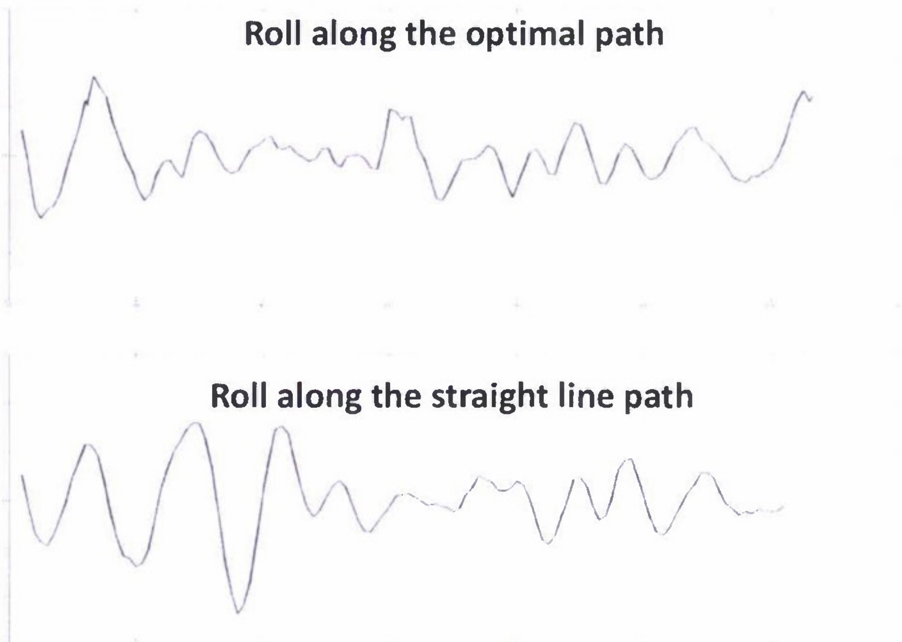

Figure 2. Time History of Roll Motion Along Optimum and Straight Line Paths. RMS Roll Reduction 106%, Increase Travel Time 6%

While work on the quasi-steady approach has been completed, we are waiting for experimental results that can be used for validation. There are many experimental results for ship motions while maneuvering in a seaway that have been obtained from free running models in a maneuvering basin. Unfortunately, while the motions are easily measured, the wave time history in the vicinity of the ship is very hard (if not impossible at the present time) to determine. Validation of any seakeeping/maneuvering code requires both the ship motions and the precise time-history of the wave input. Consequently, no experiments are available for validation.

To date, two controllers have been incorporated into the UMBEST code. As discussed in the next section, further work is continuing on developing better controllers. The first controller was a simple approach of artificially applying a force and moment on the vessel that is equal and opposite to the mean second order wave forces and moments that act on the vessel. While not very robust or efficient, the controller was adequate and did allow us to compute the motions in all six degrees of freedom. In following seas, where the frequency of encounter can go to zero, there is a problem in that the damping in potential flow goes to zero which in turn can lead to directional instabilities. In reality there is viscous damping even at zero frequency. To overcome the problem, we have incorporated a simple model first proposed by Bailey et al. (1998) and more recently used by Fossen and Smogeli (2004) or Fossen (2005). The conventional maneuvering derivatives such as Y_v and N_r are evaluated at zero frequency. The simple model is to approximate the viscous damping at zero frequency by setting it equal to the negative of the values of the stability derivatives. At other frequencies, a linear ramp is used to make the viscous contribution tend to zero at some predetermined frequency selected by the user. Based on comparisons with experiments, Fossen and Smogeli (2004) use a nondimensional cut off frequency (ω sqrt(g/L)) of 12.5. At present, we are using the semi-empirical approximations of Clarke et al. (1982) to compute the stability derivatives.

In Maki et al. (2010), the predictions of UMBEST are compared with CFD calculations for a pure sway PMM test for the S-175 containership at a Froude number of 0.275. Experimental results from Okhusu (1983) are also plotted in the figures. The CFD results were obtained using OpenFOAM, a cell-centered finite-volume method.

An example of the results from Maki et al. (2010) is shown in figure 3. Figure 3 presents the damping coefficients for sway and yaw as a function of frequency. The experimental results are shown as green circles. The CFD results are red triangles and UMBEST is the solid blue line. Also shown on the figure are the zero-frequency maneuvering coefficients given by the approximations developed by Clarke et al. (1983). The red dotted line is a composite of the UMBEST results plus an exponential ramp function that equals Clarke's result at zero frequency and goes to 10% of its value at a nondimensional frequency of 5. As can be seen, the CFD results agree well with the experiments. The potential flow calculations of UMBEST have the proper character, but are off in magnitude. Adding of the viscous zero-frequency correction helps in all the cases except B_{62}. Obviously, more research needs to be done to develop a good viscous correction for the horizontal plane potential flow computations.

UMBEST as presently configured is valid for translation along a straight line path. Research is proceeding to expand the code for maneuvering in a seaway. We have changed the formulation from an axis system moving along a straight line path to a hydrodynamic axis that follows the path of the ship. The x-y plane of the hydrodynamic axis system is coincident with the calm waterplane. The z-axis is positive upwards. Thus, the hydrodynamic axis only translates in the x_o, y_o directions, where the (x_o, y_o, z_o) system is fixed to the earth on the calm water plane. It is also free to yaw following the calm water plane projection of the body x-axis. The origin of the hydrodynamic axis is coincident with calm water plane projection of the body axis origin. The new code has been tested for zero forward speed (i.e. the case of a ship drifting in incident waves). An example of the results is shown in figures 4-9 for a box barge drifting down wave. The S-175 container ship has also been run, but the convergence tests have not yet been completed. The barge has dimensions of length = 100m, beam = 20m and draft = 10m. The

waves have a wavelength of 171m, a period of 10.5s, and height of 3m. The barge is initially in stern quartering seas with a wave heading angle of 45 degrees. In figure 4, the surge, sway and heave motions are plotted as a function of time. As can be seen, the sway and surge motions quickly settle into a constant drift velocity in the down wave direction. The motions look flat in figure 4 due the scale of the graph, but in fact they all oscillate at the wave frequency. This is clearly illustrated by the expanded scales of figure 6, in which the heave oscillates with the wave frequency at an amplitude 1.5 times larger than the wave amplitude.

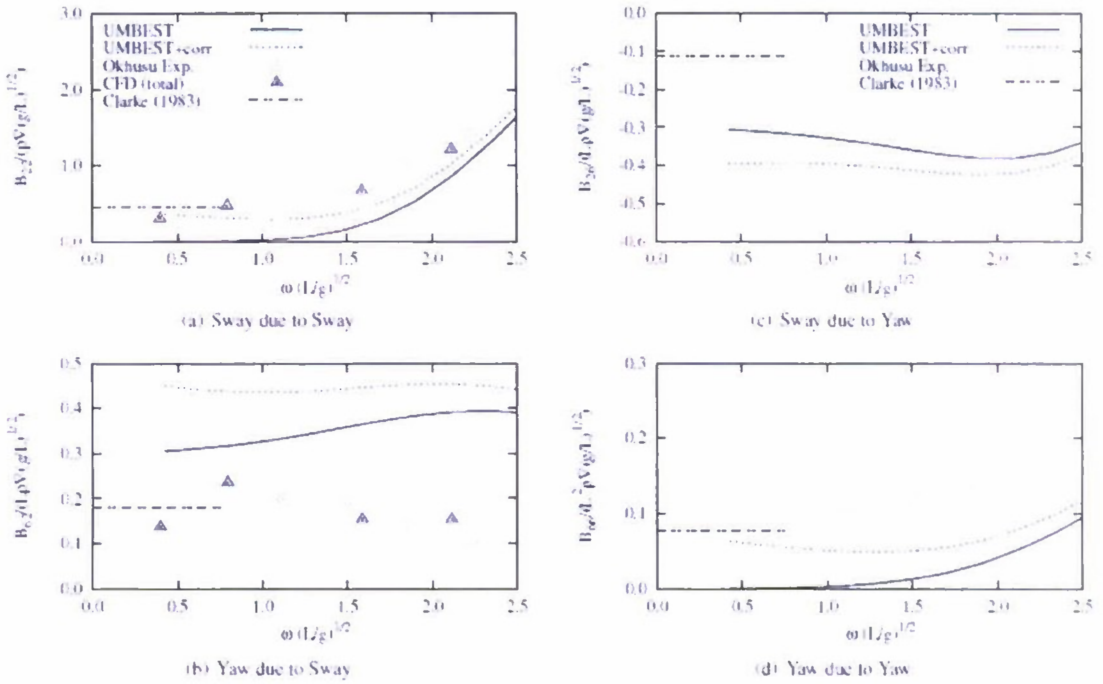

Figure 3. S-175, Fn= 0.275, damping coefficients with semi-empirical values from Clarke et al. (1983)

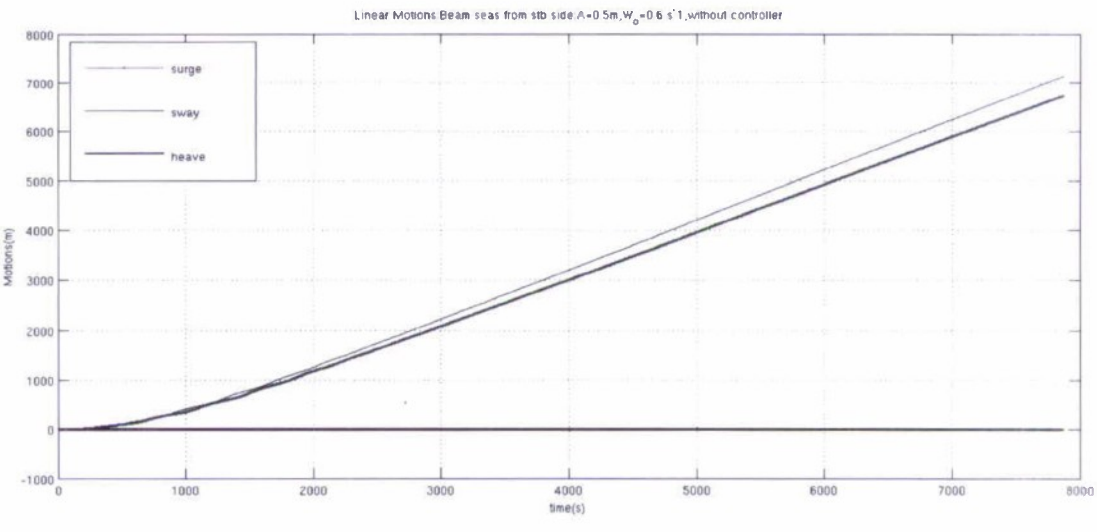

Figure 4. Box Barge Drifting in Sway, Surge and Heave Positions as a Function of Time. Wavelength = 171m, Wave Period = 10.5s, and Wave Height = 3m.

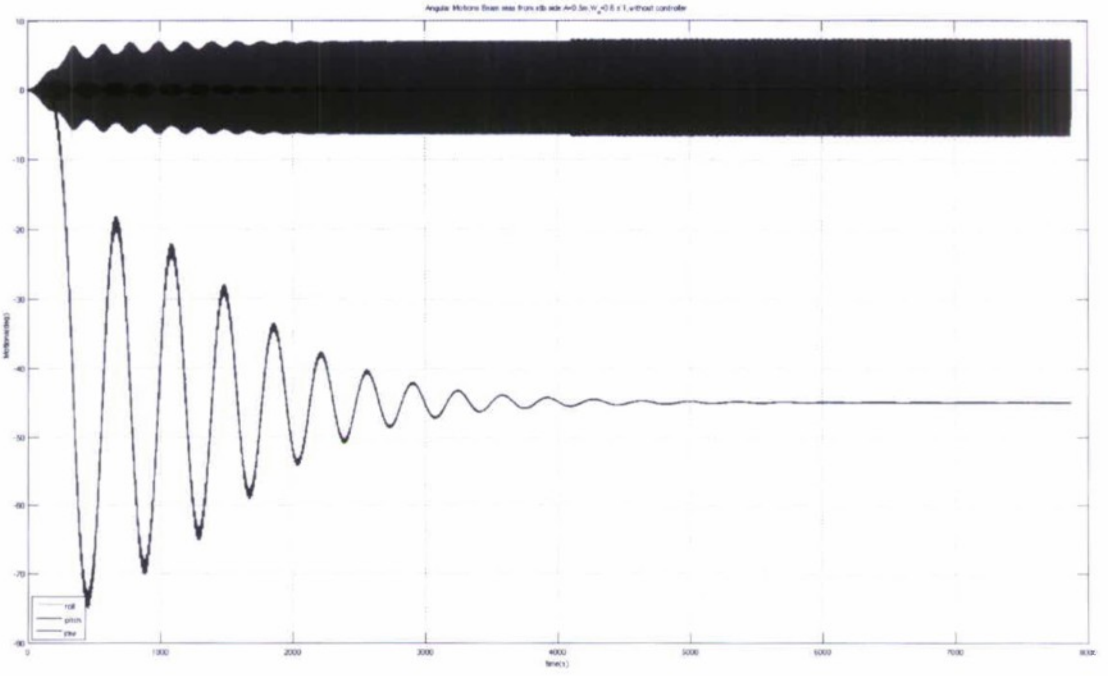

Figure 5. Box Barge Roll, Pitch and Yaw Motions as a Function of Time. Wavelength = 171m, Wave Period = 10.5s, and Wave Height = 3m.

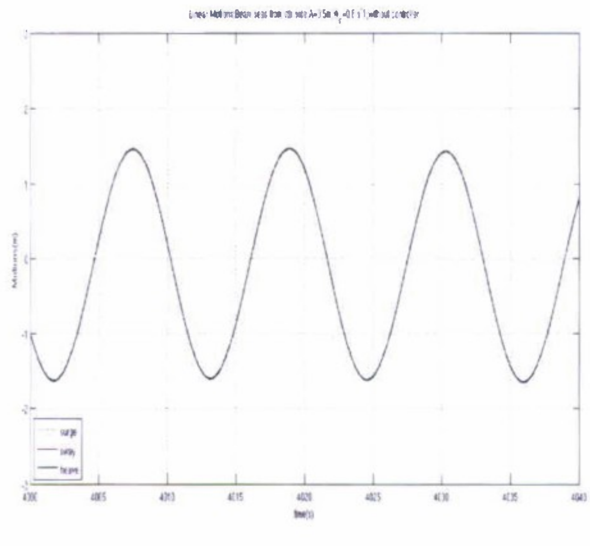

Figure 6, Detail of Heave Motion from Figure 4

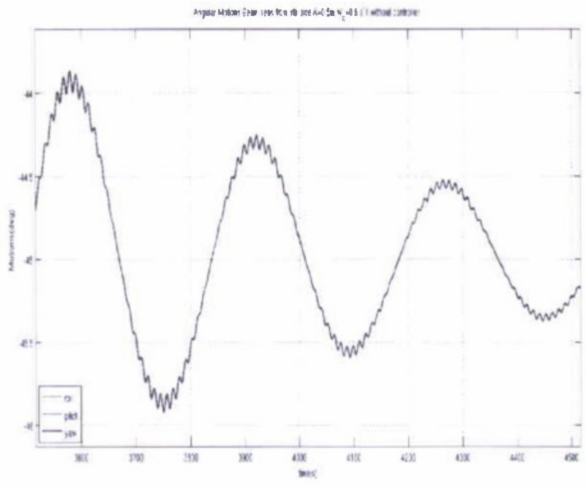

Figure 7, Detail of Yaw Motion from Figure 5

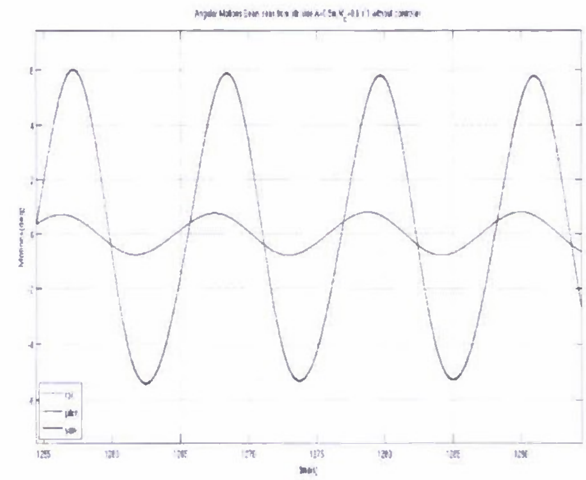

Figure 8. Detail of Roll/Pitch Motions from Figure 5

Figure 5 shows the rotational modes of motion—roll, pitch and yaw. There is clearly an oscillation with the wave frequency as shown in the expanded scales of figures 7 and 8. However, the most prominent features of figure 5 are the low frequency oscillations that die out after a long time. Because the box barge is fore-aft symmetric, the pitch and yaw motions eventually cease while roll reaches a steady state value. The yaw comes to rest in beam seas at a heading of -45 degrees. The periods of oscillation are different for the three modes of motion. This nonlinear behavior would not be seen in a purely linear ship motion code. It is the result of the body-exact force computations, the velocity squared terms in the Bernoulli equation, and the nonlinearities in the Euler equations of motion.

Another interesting feature of the results is that the period of oscillation for the high frequency motions has a mean of approximately 11.5s which is longer than the 10.5s wave period. The reason for this shift is the frequency of encounter. As shown in figure 9, the track of the ship is down wave at an angle of 46.5 degrees and a drift velocity of approximately 1.4 m/s. As shown in figure 5, after sufficient time the barge is oriented at an angle -45.0 degrees, perpendicular to the waves.

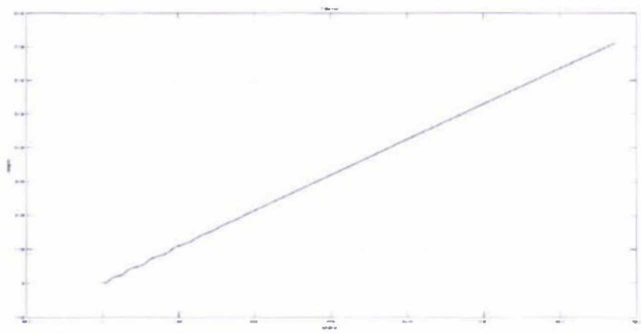

Figure 9. S-175 Track Due to Wave Drift Forces. The Waves Are Coming from the Lower Right Hand Corner.

A much improved controller has been developed by Zhen Li et al. (2010) for the path following work in the MURI project and has been incorporated in to UMBEST. The Model Predictive Control is designed to work well in a wave field with its wave frequency excitation and mean second order drift forces. The form of the controller is

$$\delta = -C_1e-C_2\psi-C_3r-C_4U\sin\psi$$

where e = cross track error
ψ = heading angle error
r = yaw rate
U = forward speed
C1, C2, C3, C4 = adjustable control constant gains

The gains are derived for stability of the control system with minimum steady state error and a quick response in the way of minimum overshoot. Details of the controller development can be found in Li et al. (2010). In the runs done to date, the controller seems to be robust and effective.

Figures 10 and 11 are examples of the predictions for the S-175 in stern quartering seas with a ship speed of 10 m/s and a wave amplitude of 1.5m. Figure 10 shows the track of the midship point both with and without the controller. Notice that without the controller, the ship quickly veers off course and it is impossible to determine the ship motions for a constant path relative to the waves. With the controller, the ship stays on course with small sway and yaw motions due to the waves. Figure 11 is an expanded view of the sway (red) and yaw (green) motions as a function of time when the controller is operating. As can be seen, there is very little, if any drift in the sway and yaw motions.

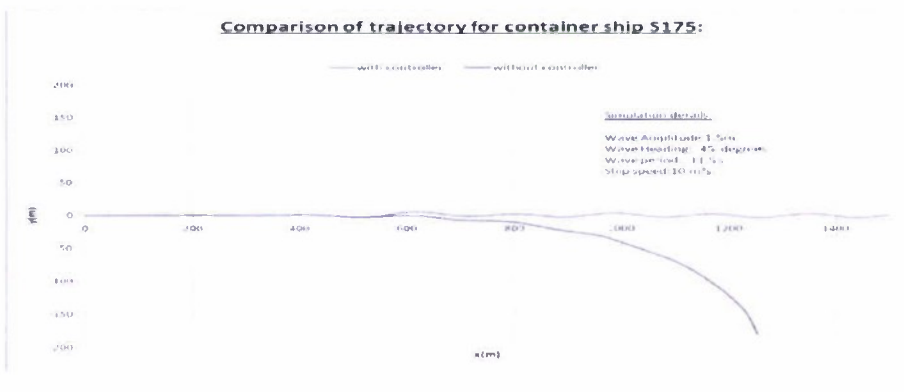

Figure 10 Trajectory for S-175 in stern quartering seas, Fn = .24

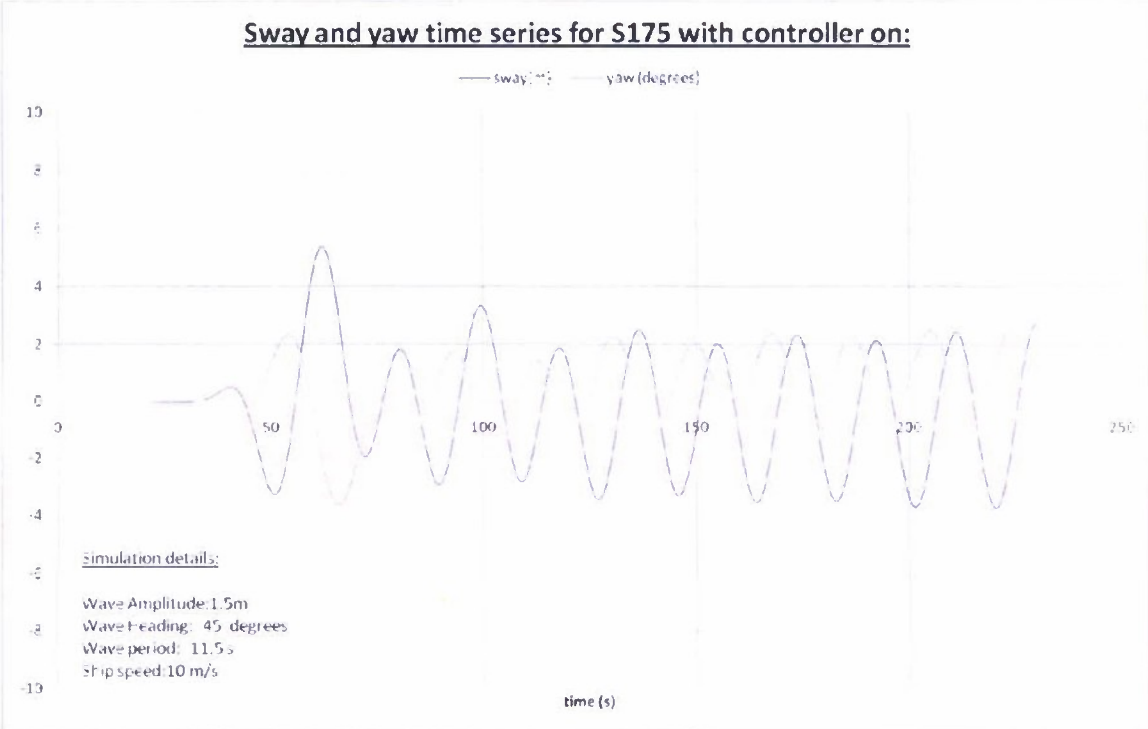

Figure 11 Sway and yaw amplitudes as a function of time for S-175 in stern quartering seas, Fn=.24

References

Bailey, P. A., W. G. Price, and P. Temarel (1998) "A Unified Mathematical Model Describing the Manoeuvring of a Ship Travelling in a Seaway," *Transactions* RINA 140, 131–149.

Clarke, D., P. Gedling, and G. Hine (1982) "The Application of Maneuvering Criterion in Hull Design Using Linear Theory. Transactions RINA.

Fossen, T. I. (2005)."A Nonlinear Unified State-Space Model for Ship Maneuvering and Control in a Seaway" *International Journal of Bifurcation and Chao,* 15 (9), 2717–2746.

Fossen, T. I. and O. N. Smogeli (2004) "Nonlinear Time-Domain Strip Theory Formulation for Low-Speed Manoeuvring and Station-Keeping," *Modeling Identification and Control,* 25 (4), 201–221.

Li, Z., Sun, J. and Beck, R.F. (2010) "Evaluation and Modification of a Robust Path Following Controller for Marine Surface Vessels in Wave Fields," *Journal of Ship Research,* Vol. 54, No. 2.

Maki, K.J., Bandyk, P.J., Beck, R.F. (2010) "Frequency Dependence of Large-Amplitude Horizontal-Plane Motion," *Proceedings*, 28th Symposium on Naval Hydrodynamics, Pasadena, California.

Control for Integrated Seakeeping and Maneuvering

Jing Sun and Soryeok Oh, University of Michigan

The objectives of this task are to develop control systems that will enable safe and effective ship maneuvering operations in a seaway while satisfying seakeeping constraints, and to develop numerical tools that can facilitate system level integration of maneuvering and seakeeping functions. This effort is also aimed at supporting the validation and verification of the blended time-domain model. Our research activities have been focused on developing and evaluating control systems that can provide improved performance for the integrated seakeeping and maneuvering system. Three different control schemes have been designed, analyzed, and evaluated, including a dynamic surface control (DSC) to complement the back-stepping design, an integrated maneuvering and seakeeping control to mimic good helmsman's behavior, and a line-of-sight (LOS) based model predictive control to enforce constraints. Numerical (i.e., simulation models) and experimental (model ship) tools are also developed to support and complement the analytical investigation.

This report will summarize the main results in the following three different areas: (1) Model ship test-bed construction and mathematical model development; (2) Control design for integrated seakeeping and maneuvering; and (3) LOS model predictive control with constraint enforcement capability.

Model ship test-bed construction and its system identification: In order to provide a test platform to support the modeling work and facilitate the control development, a free running model ship has been developed. This model ship is propelled and steered by two propulsion motors and two rudder motors, respectively, powered by batteries packed onboard. Real time control is performed by an embedded processor, with control algorithms being programmed on a hosting PC and communicated through a wireless network. Sensors for the ship motion are integrated for feedback control and data acquisition. A picture of the instrumented model ship is shown in Figure 12.

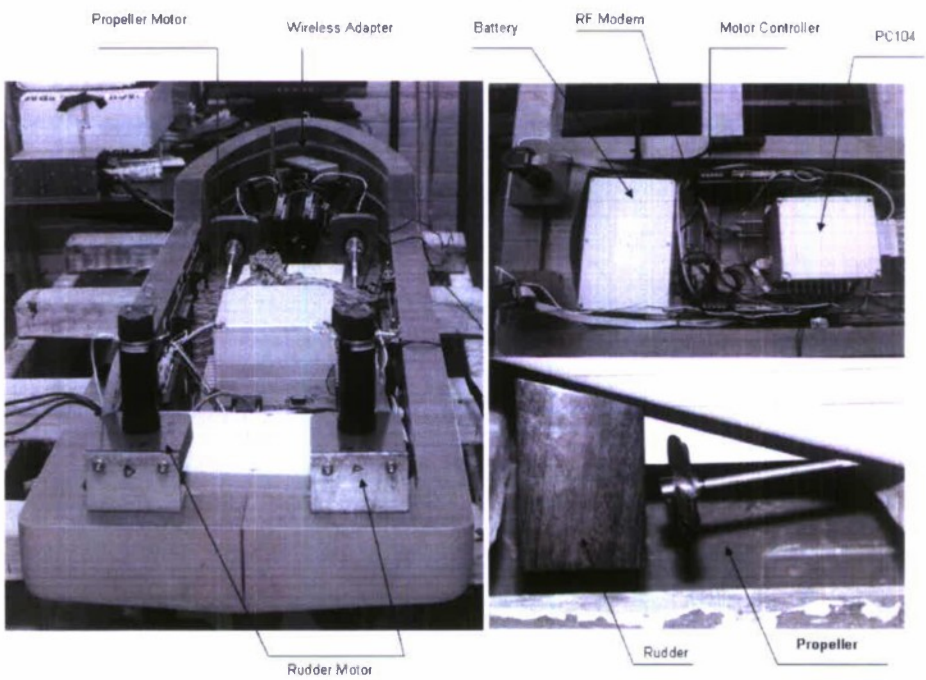

Figure 12: Instrumented model ship with propulsion motors and rudders.

Mathematical modeling for the model ship was followed to provide a numerical tool to support the control design work. System identification was performed to develop the model using experimental data sets collected from a series of well-designed tests, and additional extensive tests were performed to validate the model. The model ship and the associated simulation model served a critical role in control system development and performance evaluation. The Detailed system identification results have been documented in a paper published in *ASME/IEEE Transactions on Mechatronic* (Oh et al, 2010).

Control design for integrated maneuvering and seakeeping: Our initial control design goal was to develop a feedback control system that could mimic a good helmsman's behavior. To this end, a hierarchical control structure was defined as shown in Figure 13. It consists of an outer loop guidance law and an inner loop heading feedback control law. Stability of the closed loop system was analyzed, and the convergence rate was derived in an explicit form for the path following error.

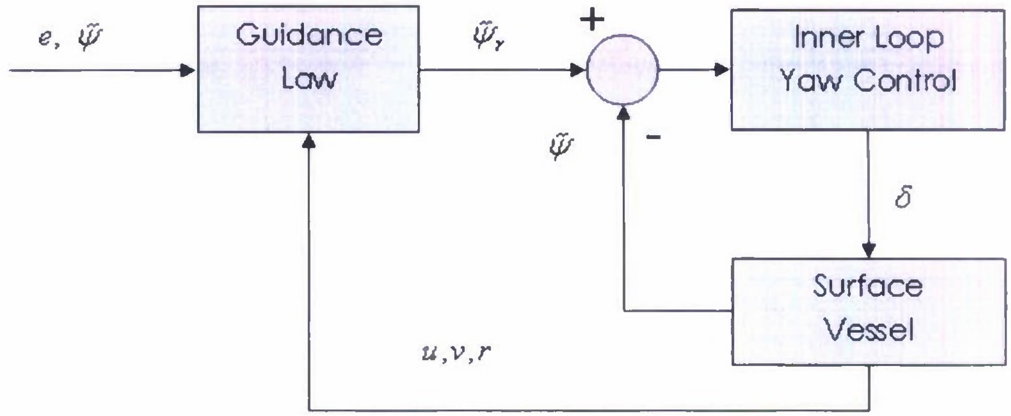

Figure 13: A hierarchical control scheme that mimics good helmsman's behavior. $\tilde{\psi}$, e are the heading angle and tracking errors respectively; ψ, ψ_r are the actual and reference heading respectively, and δ is the rudder angle.

Experimental validation was carried out to confirm the analytical and numerical results using the model ship testbed. As an example, Figure 14 shows the test results of the hierarchical control performance where path following (in terms of tracking error and heading error converging to zero) is achieved. The first plot in Figure 14 shows that the vessel converges to the path (the path is shown as the dashed line for the y-position in the top plot of Figure 14) and the cross-track error (e) converges exponentially to zero. We can also see in Figure 14 that the control input rudder saturates during the transients. The second plot in Figure 14 shows that the yaw angle ψ tracks the commanded yaw angle ψ_r which is generated by the guidance law.

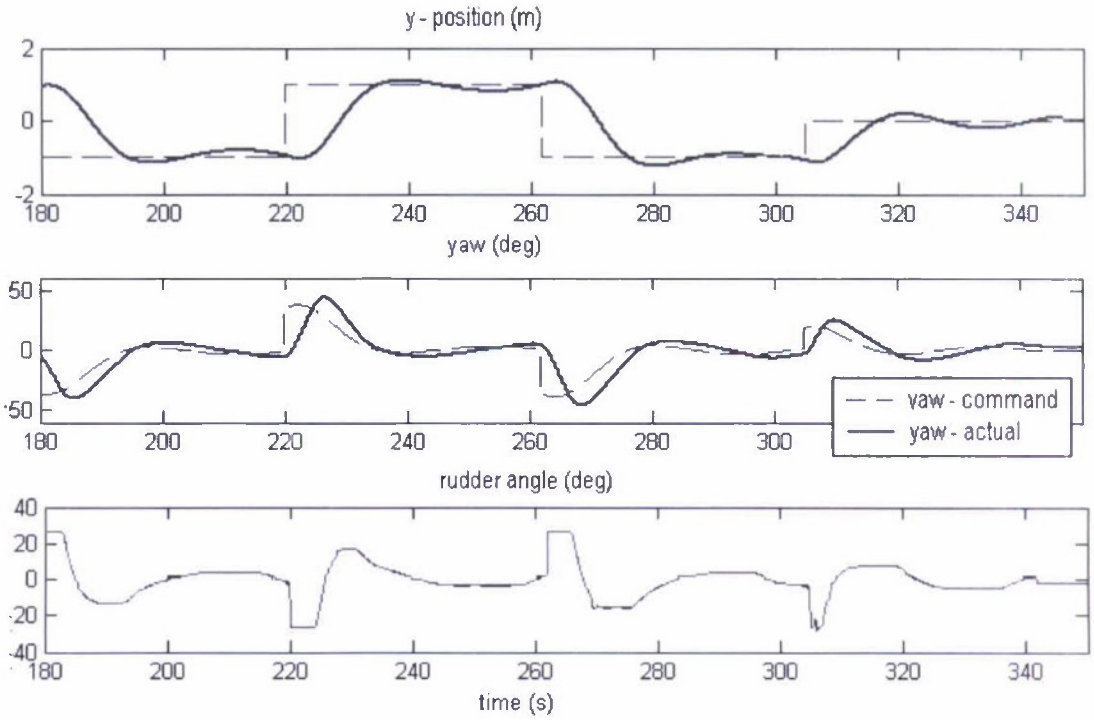

Figure 14: Experimental results of the hierarchical control that mimic a good helmsman's behavior

Development of the model predictive control for ship maneuvering with rudder amplitude/rate constraints: Model predictive control (MPC) was explored to address the constraints (such as rudder limits and roll constraints) for ship maneuver operations. As the only available control approach that can explicitly handle hard constraints, MPC has very flexible formulation that can be adjusted to fit most of the performance requirements but suffers from the computational complexity problem. Over the past two years, this group has developed several mechanisms to reduce the computational burden of MPC, thereby making it more attractive for real-time control applications. Leveraging on those results, efforts have devoted to explore the applications of MPC for ship path following control.

Complement to the MPC work within the MURI project, which addresses the ship path following in seaways, this work considers the Line-of-sight (LOS) based path following problem and develops the MPC to incorporate limits on both rudder amplitude and rate of changes. For the first two years, a linear MPC, which is computationally less demanding than its nonlinear MPC counterpart, was formulated to mimic a good helmsman behavior, and its performance was evaluated through extensive simulations.

The new development of the integrated control system in the last project year mainly focused on the algorithm enhancement. More specifically, we explored the design degree-of-freedom offered by both MPC and LOS. A new algorithm was developed to embed the LOS guidance parameter in the MPC controller design as an additional decision variable and its utility was explored through simulations. The underlying idea of changing the LOS vector norm to improve the convergence of the LOS algorithm has been also employed in a previous work (Moreira, et al., 2007), but not in the optimization framework. To our knowledge, this is the first result that combines the MPC control design with the LOS guidance scheme for a surface vessel path following under limited rudder deflection and rudder rate.

The general concept of LOS based path following control with way-point is shown in Figure 15, where the LOS angle is defined. The path following capability of a vessel motion control system is usually achieved using rudder only. Because the maximum deflection and turning speed often limit the control authority of the rudder, the control signal can easily place the rudder to operate at its limit during transients. The large rudder motion often causes adverse effects on the maneuvering performance and ride quality as they induce large roll motion. The proper planning of the vessel trajectory can be an alternative solution to alleviate the excessive rudder motion and thereby decreasing the period of rudder saturation time.

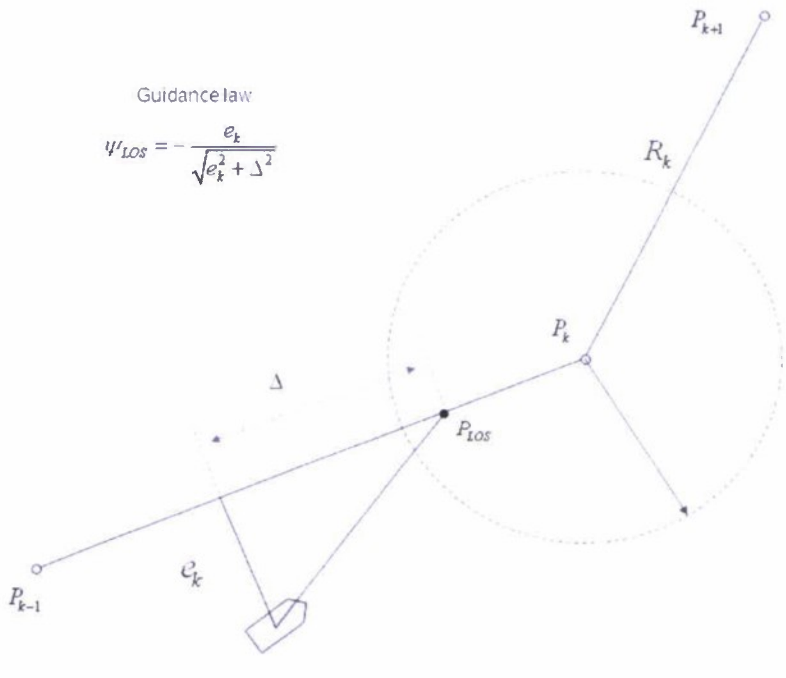

Figure 15: LOS guidance for path following with way-points

The LOS-based control using standard MPC determines the control sequence by minimizing the following cost function

$$\Phi_k = \sum_{j=1}^{N} \dot{x}_{k+j}^T Q \dot{x}_{k+j} + \dot{u}_{k+j-1}^T R \dot{u}_{k+j-1} \ .$$

where x and u are the state and control input respectively, and Q and R are weighting matrices that can be used to tune the control system for desired performance. Instead of the standard MPC formulation, we define the new LOS angle as

$$\psi_{LOS} = -(1+\bar{l}_k)\frac{e_k}{\sqrt{e_k^2+\Delta^2}}$$

with a new parameter $\bar{l}_k$ and consider the following augmented cost function

$$\Phi(k) = \sum_{j=1}^{N} (\dot{x}_{k+j}^T Q \dot{x}_{k+j} + \sum_{j=1}^{N} \dot{u}_{k+j-1}^T R \dot{u}_{k+j-1}) + L\bar{l}_k^2$$

where the LOS look-ahead distance is considered as an additional decision variable in MPC design. Our studies showed that incorporating this additional parameter in the optimization

provides substantial benefits in speeding up the path convergence and in eliminating overshoot. Thanks to the sequential quadratic programming (SQP) and the linear MPC used, no noticeable computational load was observed in our simulation.

Figures 16 and 17 show the simulation results of the proposed control scheme, where the response of the system with LOS as an optimizing parameter is compared with that with LOS being fixed. Better tracking performance and reduced overshoot are achieved as shown in Figure 16. Figure 17 shows the rudder deflection angle and the LOS parameter of the two simulation runs. Adjusting the LOS parameter has shortened the time period in which the rudder saturates, and consequently the ship path following overshoot has reduced significantly. The CPU time required to compute the SQP solution for both methods on a 2.2 GHz Pentium 4 PC with 2G RAM are around 0.0234 sec, which indicates that the proposed MPC algorithm is applicable and the real-time implementation for the ship path following is possible.

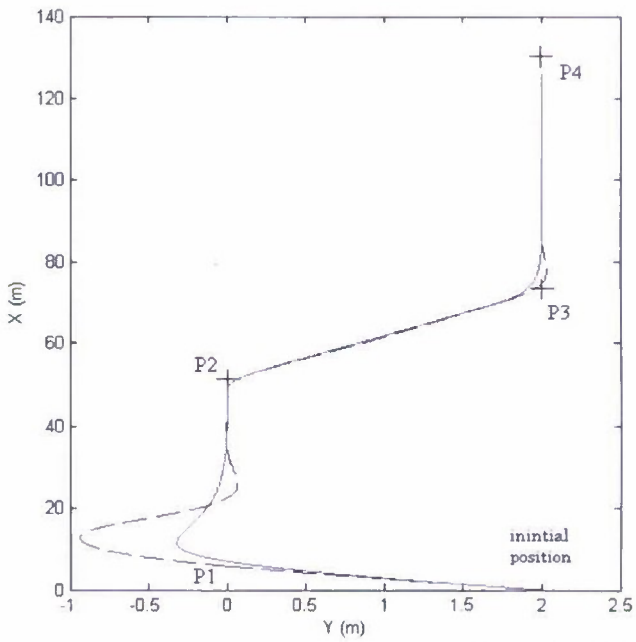

Figure 16 Vessel trajectory in the x-y plane with fixed LOS (dashed line) and variable LOS (solid line) MPC path following control

Detailed results of this work have been documented in a journal paper that has been published in the *IEEE Transactions on Ocean Engineering* (Oh and Sun, 2010).

References

Soryeok Oh, Jing Sun, Zhen Li, Ed A. Celkis and D. Parsons (2010), "System Identification of a Model Ship Using a Mechatronic System," *IEEE Transactions on Mechatronics*, Vol. 15, No. 2, pp316-320, April 2010.

Moreira, L., Fossen, T. I., Soares, C. G. (2007), "Path Following Control System for A Tanker Ship Model," *Ocean Engineering*, Vol. 34, pp. 2074-2085, 2007.

Soryeok Oh and Jing Sun (2010), "Path Following of Underactuated Marine Surface Vessels Using Line-of-Sight Based Model Predictive Control," *Ocean Engineering*, Vo. 37, (2-3), pp 289-295, 2010.

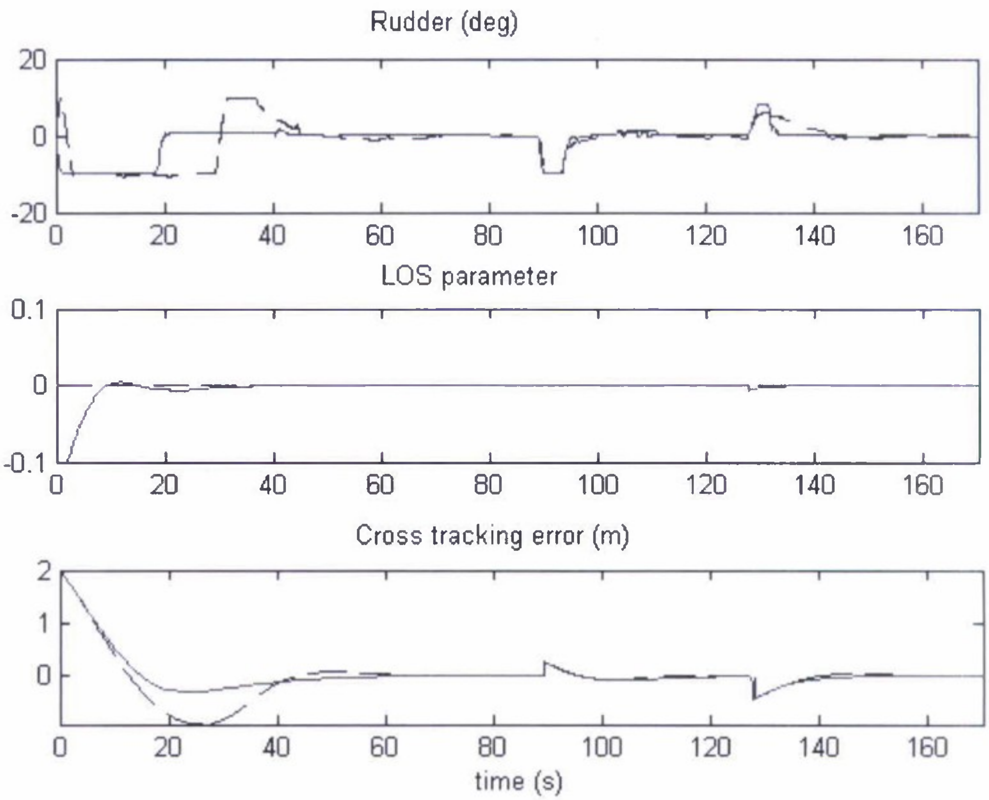

Figure 17 LOS parameter, cross tracking error, and the rudder deflection angle for fixed LOS (dashed line) and variable LOS (solid line) MPC schemes. The variation of the LOS parameter is limited to be within [-0.1 0.1]

Papers Acknowledging Support by this Research

Li, Z., Sun, J. and Beck, R.F. (2010) "Evaluation and Modification of a Robust Path Following Controller for Marine Surface Vessels in Wave Fields," *Journal of Ship Research*, Vol 54, No 2, pp 141-147

Zhang, X., Bandyk, P. and Beck, R.F. (2010) "Seakeeping Computations Using Double-Body Basis Flows," accepted for publication in *Applied Ocean Research*

Bandyk, P. and Beck, R.F. (2010) "The Acceleration Potential in Fluid-body Interaction Problems," accepted for publication in *Journal of Engineering Mathematics*

Bandyk, P. and Beck, R.F. (2008) "Nonlinear Ship Motions in the Time Domain," *Proceedings*, 27th International Conference on Offshore Mechanics and Arctic Engineering, Estoril, Portugal.

Bandyk, P. and Beck, R.F. (2009) "Nonlinear Ship Motion Computations Using a Time-Domain Body-Exact Slender-Body Approach," *Proceedings*, 28th International Conference on Offshore Mechanics and Arctic Engineering, Honolulu, Hawaii.

Bankyk, P, Beck, R.F., Zhang, X. (2010) "Applications of the Ogilvie-Tuck Formulae to Ship Hydrodynamics," *Proceedings*, 29th International Conference on Offshore Mechanics and Arctic Engineering, Shanghai, China.

Zhen Li, Jing Sun, Soryeok Oh (2009), "Design, Analysis and Experimental Validation of a Robust Nonlinear Path Following Controller for Marine Surface Vessels," *Automatica*, Volume 45, Issue 7, July, pp1649-1658.

Soryeok Oh, Jing Sun, Zhen Li, Ed A. Celkis and D. Parsons (2010), "System Identification of a Model Ship Using a Mechatronic System," IEEE Transactions on Mechatronics, Vol. 15, No. 2, pp316-320, April 2010.

Soryeok Oh and Jing Sun (2010), "Path Following of Underactuated Marine Surface Vessels Using Line-of-Sight Based Model Predictive Control," *Ocean Engineering*, Vo. 37, (2-3), pp 289-295, 2010

Zhen Li, Jing Sun, So-ryeok Oh (2009), "Path Following for Marine Surface Vessels with Rudder and Roll Constraints: An MPC Approach," *Proceedings of the 2009 American Control Conference*. St. Louis, MO, June, 2009.

Soryeok Oh, Jing Sun, and Zhen Li (2008), "Path Following Control of Underactuated Marine Vessels via Dynamic Surface Control Technique," *Proceedings of the ASME 1st Control Conference*, October, 2008.

Zhen Li, Jing Sun, and Soryeok Oh (2007), "A Robust Nonlinear Control Design for Path Following of an Under-actuated Marine Surface Vessel," *Proceedings of the 2007 IFAC Control Applications to Marine Systems (CAMS'07)*, September, 2007.

Students Support by this Research

James Wolfe, MSE 2007

Piotr Bandyk, Ph.D., Thesis entitled *A Blended Method Body-Exact Approach to Ship Motions*, 2009

Rahul Subramanian, Ph.D., *Body-Exact Theory for Maneuvering in a Seaway*, expected graduation 2012

Soryeok Oh, Post-Doctoral student, 2005 -